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# RFI mitigation strategies for next generation phased array radio telescopes

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## Abstract

The Low-Frequency Array (LOFAR) telescope is a phased array radio telescope that observes weak astronomical signals in-between strong terrestrial radio frequency interference (RFI). The RFI causes intermodulation products in the analog system due to the non-linearity of the electronic devices used. Multiple strategies are implemented in LOFAR to mitigated the RFI and their intermodulation products: RFI is suppressed in the analog domain based on their direction-of-arrival, using analog beamforming, and based on their frequency, using notch and bandpass filters. The intermodulation products are minimised by using a very linear signal chain, using several stages of low-gain, high-linearity amplifiers. However, in some LOFAR observations, the intermodulation products add in-phase during beamforming, limiting the sensitivity of the telescope. It is shown how this can be prevented by adding different time delays to each signal before digitisation.

## 1 Introduction

Although only a few frequency bands are reserved for radio astronomy [1], radio telescopes also observe in bands allocated for other primary usage, at times and locations where these bands are not used. The Low-Frequency Array (LOFAR) telescope [2] observes the entire UHF band with a phased array, making use of a large number of broadband receivers, and forming beams in several directions and frequency bands simultaneously.

Each LOFAR antenna not only receive the astronomical signals of interest, but almost all local UHF transmissions, which is considered RFI. These RFI signals can be up to 100 dB stronger than the astronomical signals. As an example, Figure 1 shows the LOFAR 110-190 MHz band which contains two strong DAB+ signals and a number of intermittent communication transmissions. LOFAR uses several RFI mitigation techniques [3, 4, 5], mostly in the digital domain, to use the free spectrum, in time and frequency, between these transmissions for astronomy observations. However, any non-linearity in the RF system causes the strong RFI signals (in-band and out-of-band) to form intermodulation products (IMPs) in the free spectrum, which are difficult to remove afterwards.

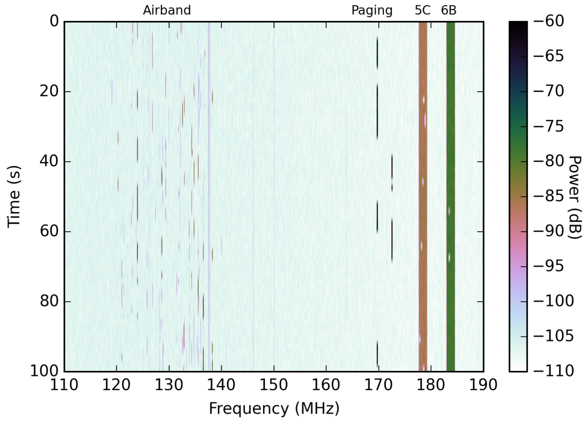

**Figure 1.** RF spectrum at the LOFAR core measured with a HBA front-end. 5C and 6B are two DAB+ channels.

During the last decades, several new digital broadcast systems have been rolled out that pose new challenges for radio telescope systems. DAB+ and DVB-T make use of OFDM (orthogonal frequency division multiplexing), consisting of several thousand, narrow-band sub-carriers giving them a broad bandwidth. For example, each DAB+ channel consist of 1536 sub-carriers of 1.537 kHz each, with a symbol duration of 1.246 ms (about 400 km in air) [6]. National coverage is achieved by using multiple synchronised transmitters that transmit the same data at the same frequency, with a maximum distance of about 74 km between transmitters. The result is that, even on long baselines, the signal received by different elements are coherent.

LOFAR is able to achieve a good sensitivity by using thousands of elements in a phased array, in which the signals are added coherently, but the noise of each receiver is added incoherent. However, because the whole array receive coherent DAB+ transmissions, the IMPs generated by each receiver can also add coherently. Figure 2 shows an example of a LOFAR observation where DAB signals cause IMPs in the empty band between 140 and 170 MHz. For such observations, the sensitivity of LOFAR is not limited by noise, but by the IMPs caused by the RFI. To overcome this problem, LOFAR uses a combination of several RFI mitigation strategies that will be discussed in the next sections.

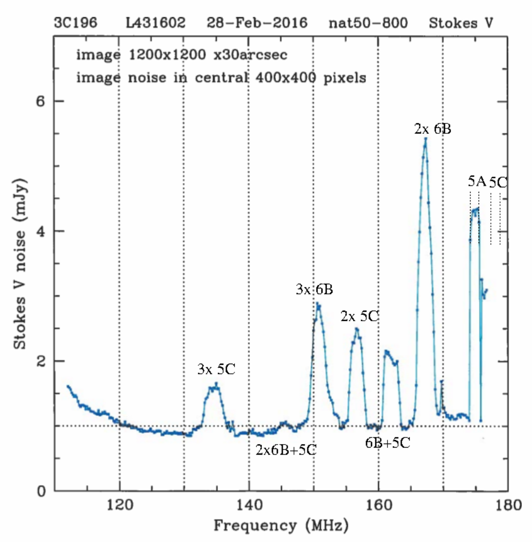

**Figure 2.** RFI intermodulation seen with LOFAR.

## 2 Reducing RFI

RFI can be suppressed in the analogue domain without suppressing the signal-of-interest by using the difference in angle-of-arrival and frequency. Figure 3 shows the LOFAR High-Band Antenna (HBA) RF chain, where the blue components reduce RFI based on arrival direction and the red components based on frequency. Figure 4 shows the sky-noise signal (black line) and RFI (red and magenta line) power in the 110-190 MHz band through the RF chain. At the LOFAR core, the integrated RFI power is about 50 dB larger than the sky-noise at the antenna. At some remote stations it is even worse.

**Antenna gain:** LOFAR uses a differential antenna that has maximum gain towards zenith and minimum gain towards the horizon. The antennas are also placed low, i.e. on the ground, to limit their gain towards the horizon. The effect of the differential antenna is visible in Figure 4, where the balun selects the differential RFI, which is about 5-10 dB lower than the RFI in a single-ended antenna element.

**RFI Filter:** Out-of-band RFI needs to be filtered out as early as possible in the RF chain, without compromising sensitivity. However, if a filter is too early in the chain, the loss of a filter will increase the noise figure. If a filter is too far in the chain, the RFI will cause unnecessary IMPs. In LOFAR the FM signals are the major out-of-band RFI source and they cause second-order IMPs inside the HBA band if not filtered sufficiently. A cascaded approach is used, in which the FM is suppressed (just) enough before each amplifier so that the FM power (magenta line in Figure 4) is below the acceptable limits (magenta dots in Figure 4).

**Analog beam-former:** In the LOFAR HBA, an array of 4x4 antenna elements are grouped together in a tile. A variable time delay is added to each of the 16 elements before they are summed together. The signals from a given direction in the sky then add in phased (see red line), giving a gain of 12 dB, while signals from other directions and noise do not add coherently. However, the elements are on a regular grid, with 1.2 m spacing, so that at certain observation angles, a DAB transmitter may be in a grating lobe (i.e. also added coherently). In this worst-case scenario (thick red line) the RFI is not reduced by the analog beamformer. These worst-case directions can be 'blacklisted' for sensitive observations. In most observing directions, however, the RFI adds destructively (thin red line).

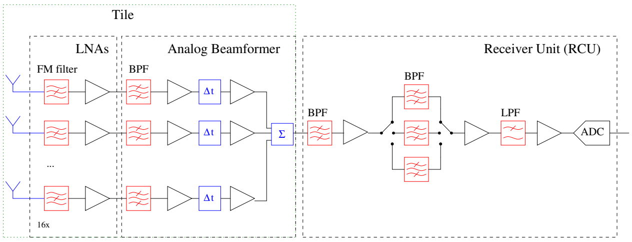

**Figure 3.** Block diagram of the LOFAR RF chain.

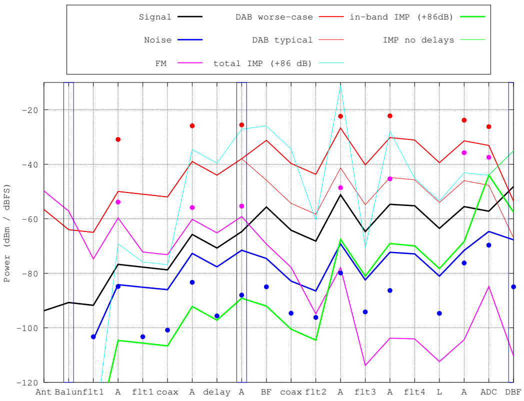

**Figure 4.** Level diagram, showing the signal, noise, RFI and IMP through a RF chain, integrated over 110-190 MHz for in-band signals, for the worst-case beam with a strong DAB+ transmitter in the tile grating-lobe and the beam in it's second-order IMP grating-lobe. .

**Bandpass filters:** Each LOFAR frequency band is less than an octave, so that most IMPs of in-band RFI fall outside the frequency band. However, to prevent these out-of-band IMPs (cyan line) from reaching the ADC, bandpass filters are needed before the ADC to only select the desired Nyquist zone.

By filtering the RFI based on direction-of-arrival and frequency, LOFAR is able to suppress the RFI by about 40 dB w.r.t. the signal, before it reaches the ADC.

## 3 Reducing IMPs

Because there will always be some RFI at each component in the RF chain, it is important that each component is linear enough to cope with the RFI. For a given amount of RFI

**Table 1.** System linearity requirements

| | | FM | DAB (6B&12C) |
|---|---|---|---|
| RFI Freq | MHz | 87-108 | 183-184, 227-228 |
| RFI Power | dBm | -40 | -69 |
| IMP order | | 2nd | 3rd |
| IMP Freq | MHz | 174-216 | 138-141 |
| Sky Noise Power | dBm | -99 | -102 |
| Max IMP Power | dBm | -149 | -187 |
| Required IIP2/IIP3 | dBm | 69 | -10 |

**Table 2.** Dynamic range budget for sub-components

| | Noise | IP3 | DR | |
|---|---|---|---|---|
| LNA | 45% | 18% | 162 | |
| BF | 36% | 32% | 160 | |
| RCU | 19% | 50% | 143 | |
| **Total** | | | 151 | |

and a specified IMP level, the required linearity of the system (Section 3.1) and its subsystems (Section 3.2) can be calculated.

## 3.1 System linearity requirements

For LOFAR, the IMPs need to be 85 dB (50 dB) below the sky noise power density at each receiver at the LOFAR core (remote stations), to be sure that no IMPs will degrade its sensitivity for deep observations. Given the known RFI levels, the required linearity can then be calculated as shown in Table 1.

## 3.2 Subsystem linearity requirements

It is useful to define a **dynamic range** parameter, which gives the dynamic range from the noise floor to the IP3, as $\mathrm{DR} = \mathrm{IIP3} - 10\log(kTB)$. For LOFAR to achieve a system temperature of $T_{\text{sys}} \approx 140$ K and an input linearity of $\mathrm{IIP3}_{\text{sys}} = 3$ dB, a dynamic range of 150 dB is required. Using the system dynamic range, the dynamic range of the subsystems can be calculated by specifying the contribution of each subsystem to the noise and non-linearity, as shown in Table 2. Note that after the analog beamformer, the RFI is assumed to be suppressed by 12 dB (w.r.t. the signal), relaxing the dynamic range requirement.

The **LNA** is the largest contributor to the system noise and is therefore designed for low noise (<1 dB NF including antenna mismatch). However, it also needs to have a large IP2, which is achieved by using a fully-differential configuration. This gives an IIP2=40 dB, which, in combination with a -30 dB FM notch filter, makes it possible to reach the 70 dB IIP2 requirement. Source degenerative feedback is used to limit the gain to about 15-20 dB. With an OIP3 of 30 dBm, it gives an IIP3 >10 dB for the LNA, resulting in a DR>160 dB as required.

For the beamformer to reach the required linearity, the **beamformer amplifiers** need IIP3 >20 dBm. However, the OIP3 of amplifiers scales almost linearly with power consumption. Given the limited amount of power available (about 300mW/amplifier), the OIP3 is limited to about 35 dBm. The only way to achieve the required IIP3 level is therefore to have amplifiers with low-gain (<15 dB). If more gain is needed due to lossy components, the required linearity is achieved by using multiple, low-gain amplifiers distributed between the lossy components.

In LOFAR, a pipelined **ADC** is used to achieve high bit resolution at a high sample rate. However, these ADCs has small differential nonlinearity errors that occur at specific code transition points in the ADC range [7]. The most significant error occur at the the transition points of the first (4-bit) ADC. This results in spurious harmonics to be larger for small (<-25dBFS) signals than for large signals. To ensure that the ADC always operate in its most linear region, a (out-of-band) dither signal needs to be added. When the same signal is sampled in parallel ADCs, e.g. when the LOFAR signal is dominated by one strong DAB+ transmitter, the ADC harmonics are coherent and can form IMP beams (see next section). By using independent dither signals for each ADC, the harmonics can be made incoherent. A more detailed analysis of the correlation of IMPs in parallel ADCs can be found in [8].

Therefore, to have an acceptably low IMP levels, the RF chain needs to have a number of low-gain, high linearity amplifiers distributed throughout the RF chain between the other lossy components. This results in the signal (black line in Figure 4) slowly increasing from the input to the ADC. This is required so that the RFI levels (magenta and red line) stay below the linearity limit of each device (magenta and red dots), while the noise of each component (blue dots) stays well below the signal.

# 4 IMPs in beamforming

Because there will always be some RFI at the ADC that will generate IMPs, these IMPs must be prevented from adding constructively during digital beamforming. In the next subsections, it is first shown why IMPs add coherently and then how this can be avoided.

## 4.1 IMP virtual beams

In a radio telescope, the input excitation is small, so that a truncated Taylor expansion $v_{\text{out}} = k_0 + k_1 v_{\text{in}} + k_2 v_{\text{in}}^2 + k_3 v_{\text{in}}^3$ is normally sufficient to write the output voltage $v_{\text{out}}$ in terms of the input voltage $v_{\text{in}}$. The two last terms are called the second and third order IMPs, or just 2nd IMP and 3nd IMP. When $v_{\text{in}}$ consist of a number of continuous wave input signals $v_{\text{in}} = \sum_i v_i cos \omega_i t$, the second order products are at the sum and difference frequencies of any combination of two input signals and the third order products are at the sum and difference frequencies of any combination of three input signals.

The last step in the analog chain is the ADC, which not only generates non-linear terms as described above, but also folds all frequencies into the Nyquist zone of interest. For example, two input frequencies, $\omega_i$ and $\omega_j$, will generate a 2nd IMP at $\omega_b = \left|\omega_i \pm \omega_j - l\omega_s\right|$ were $\omega_s$ is the sampling frequency, $l$ an integer and $\omega_b$ a frequency within the Nyquist zone that is observed. In LOFAR, the ADC samples at $f_s$ =200 MHz. The resulting 2nd and 3rd IMP of the 6B (183.648 MHz) and 5C (178.352 MHz) DAB channel in the 100-200 MHz Nyquist zone is clearly visible in Figure 2. Note that each DAB channel is about 1.5 MHz wide, so that the 2nd IMP is about 3 MHz and the 3rd IMP about 4.5 MHz wide.

It can be shown that if a beam is pointed in the direction of unit vector $\hat{n}_b$ with the RFI signals at $\omega_i$ and $\omega_j$ coming from directions $\hat{n}_i$ and $\hat{n}_j$ respectively, the 2nd IMP of all elements will add in phase when $\omega_i\hat{n}_i \pm \omega_j\hat{n}_j - \omega_b\hat{n}_b = 0$ regardless of the positions of the receiving elements. We can then say these two RFI sources have a 2nd IMP beam in the direction $\hat{n}_{b0}$, given by

$$\hat{n}_{b0} = \frac{\omega_i}{\omega_b}\hat{n}_i \pm \frac{\omega_j}{\omega_b}\hat{n}_j. \qquad (1)$$

In a regular array, the IMPs also have grating lobes around the IMP beam direction $\hat{n}_{b0}$, which potentially increases the number of directions in which the IMPs add up coherently.

### 4.2 Reducing IMP beams

When the telescope is observing in a direction of an IMP beam or grating lobe, the IMPs of the individual receiver chains add coherently. When the IMPs are from a different Nyquist zone than the signal, the in-phase addition can be prevented by adding different delays to the signal before the ADC and then removing the delay digitally after the ADC (similar to [9]). This is implemented by adding a different time delay to the analog beamformer of each tile. This will not have an effect on the signal, as the delay is added and subtracted at the same frequency. However, for the IMPs, the delay is added in one Nyquist zone ($\omega_i \pm \omega_j$) and subtracted in another Nyquist zone ($\omega_b = \left|\omega_i \pm \omega_j - l\omega_s\right|$). The delays can then be chosen such that the IMPs will cancel out (add out-of-phase) in the direction of interest.

Figure 4 (green line) shows that the ADC generates the most IMPs in the 'worst-case' scenario where a strong DAB+ signals is in a tile grating lobe so that it adds in-phase in the analogue beamformer. The thin and thick green line show the difference after the digital beamformer when the IMPs add in-phase (thin green line) and when each tile has a different time delay, in steps of $T_s/16$ =0.31ns, where $T_s = 5$ ns is the ADC sample rate (thick green line).

## 5 Conclusion

Strong RFI causes coherent intermodulation products in the analog chain of a phased array system. These intermodulation products can add in-phase for digital broadcast signals such as DAB+ when observing in certain directions. Such RFI needs to be mitigated in the analog chain so as not to limit the sensitivity of the radio telescope.

In LOFAR, RFI is mitigated by using filters that suppress out-of-band RFI and by analog beamforming that suppresses RFI based on its arrival direction. Furthermore, the RF chain is designed to be very linear by designing the system in a top-down approach. First the required system dynamic range is determined and this is then divided down to each component. The gain stages are then implemented using several stages of low-gain, high-linearity amplifiers distributed through the chain. For the directions where the intermodulation products add in-phase, different time delays for each tile can be used to move their phases apart, so that they add destructively.

These RFI mitigation strategies make it possible for a telescope like LOFAR to do radio astronomy in an environment full of man-made RFI signals.

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